Opportunities of 5G Mobile Technology for Climate Protection in Switzerland

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Opportunities of 5G mobile technology for climate protection in Switzerland

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Abstract. 5G mobile networks are intended to meet the increasing requirements placed on mobile communications. Producing and operating 5G infrastructure causes direct effects on greenhouse gas (GHG) emissions. Meanwhile, 5G is expected to support applications that contribute to GHG abatement. We investigated (i) the GHG footprint of 5G infrastructure, and (ii) the GHG abatement potential of four 5G-supported use cases (i.e., flexible work, smart grids, automated driving and precision farming) for Switzerland in 2030. Our results show that 5G infrastructure is expected to cause 0.018 Mt CO2e/year. Per unit of data transmitted, 5G is expected to cause 85% less GHG emissions in 2030 than today's 2G/3G/4G network mix. The four 5G-supported use cases have the potential to avoid up to 2.1 Mt CO2e/year; clearly more than the predicted GHG footprint of 5G infrastructure. The use cases benefit especially from ultra-low latency, the possibility to connect many devices, high reliability, mobility, availability and security provided by 5G. To put 5G at the service of climate protection, measures should be taken in two fields. First, the GHG footprint of 5G should be kept small, by installing only as much 5G infrastructure as required, running 5G with electricity from renewable energy sources, and decommissioning older network technologies once 5G is widely available. Second, the GHG abatements enabled by 5G-supported use cases should be unleashed by creating conditions that target GHG reductions and mitigate rebound effects. The final outcome depends largely on the political will to steer the development into the direction of a net GHG reduction.

Keywords: 5G, mobile networks, greenhouse gas emissions, climate protection, life cycle assessment, direct effects, indirect effects.

1 Introduction

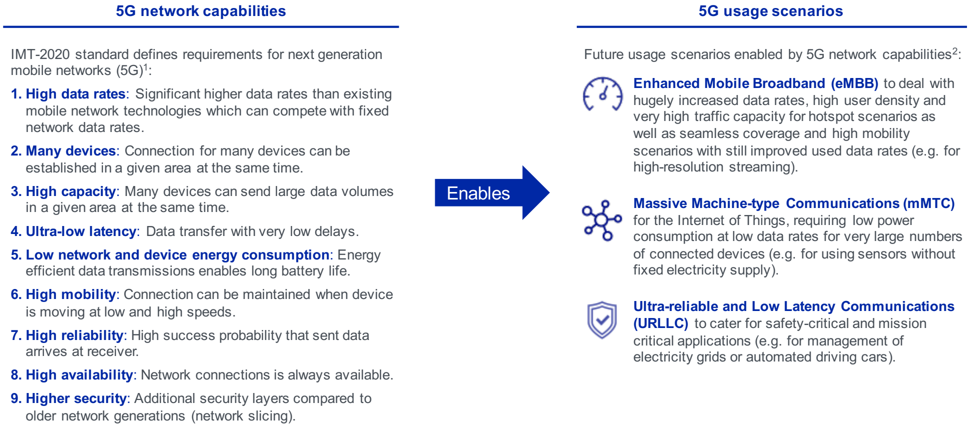
Requirements placed on mobile networks are increasing. The monthly mobile data traffic per user in Western Europe is expected to increase from 2.4 GB in 2017 to 12 GB in 2022 [1] and the global number of mobile connections to increase from 8.6 in 2017 to 12.3 billion in 2022 with a growing share of Internet of Things (IoT) connections [2]. New mobile applications impose additional network requirements. For example, sensors to monitor (safety-)critical infrastructures (e.g. in connected vehicles) require energy-efficient, reliable and secure data transfer. To specify the requirements placed on the next generation of mobile networks, the International Telecommunication Union (ITU) developed three mobile network usage scenarios [3] and a set of minimum requirements [4], which became a standard for requirements of the 5th generation of mobile networks (5G, Fig. 1).

The climate impacts of mobile networks, as of any kind of information and communication technology (ICT), can be traced back to their direct and indirect effects on greenhouse gas (GHG) emissions. Direct effects refer to the emissions caused throughout the life cycle of ICT hardware; in the case of mobile networks the emissions caused by producing, operating and disposing of the network equipment. In Switzerland, almost 19’000 mobile communication installations (e.g. mobile base stations) were in operation in 2018 [6]. Indirect effects refer to the changes caused by applying ICT to other processes and consequences for the related GHG emissions. These indirect effects can be favorable or unfavorable for climate protection [7]. For example, 4G network data rates provide the possibility for mobile work (e.g. on trains) with consequences for transport demand, modal split in transport and the related GHG emissions; an impact that was unthinkable with 2G networks. The enhanced capabilities provided by 5G mobile networks (listed in Fig. 1) are expected to support several (new) use cases, with potential consequences for GHG emissions [8].

Since many years, researchers assess and discuss the direct environmental effects of ICT products and services [9–16] with some of them focusing on mobile networks specifically [17–22]. Scharnhorst et al. [22] compared the environmental footprint of 2G and 3G mobile networks and found that 2G networks (GSM) perform better than 3G networks (UMTS) for the impact category of climate change. In a more recent study, Malmodin and Lundén [21] found that the operation of global telecommunication networks (fixed and mobile networks) caused 169 Mt CO2e in 2015. To date, no scientific studies on the GHG footprint of 5G mobile networks are reported in literature. Some studies on environmental impacts of 5G mobile networks in other countries have been published in grey literature [23,24].

Indirect effects of ICT on GHG emissions, specifically the potential of ICT applications to avoid GHG emissions (ICT GHG abatement potential) have been investigated for many years as well. For example, the Global e-Sustainability Initiative (GeSI), together with Accenture Strategy, estimated that ICT applications in the buildings, transport and energy sector have the potential to avoid up to 20% of global GHG emissions in 2030 [25]. In a similar study, Malmodin and Bergmark [26] estimated that this potential lies between 7.4% and 15.3%. Regional studies showed that ICT applications can avoid between 19.1 and 36.0 Mt CO2e in Canada in 2020 [27], and between 0.72

and 6.99 Mt CO2e in Switzerland in 2025 [28]. Telecommunication network operators as well estimated the GHG abatement potential of their product and services. For example, British Telecom (BT) estimated that in 2019/20 their customers avoided 3.1 times more GHG emissions by using BT products and services than BT causes itself [29] and Swisscom estimated a factor of 2.87 in 2020 [30]. Many further studies on the GHG abatement potential of ICT can be found in the literature, e.g. [31–40], for an overview see [41]. Some technology providers and consulting companies have already investigated indirect effects of 5G on GHG emission in other countries [42,43]; however, we could not find a study published by the scientific community.



5G network capabilities

IMT-2020 standard defines requirements for next generation mobile networks (5G)[1]:

1. **High data rates**: Significant higher data rates than existing mobile network technologies which can compete with fixed network data rates.
2. **Many devices**: Connection for many devices can be established in a given area at the same time.
3. **High capacity**: Many devices can send large data volumes in a given area at the same time.
4. **Ultra-low latency**: Data transfer with very low delays.
5. **Low network and device energy consumption**: Energy efficient data transmissions enables long battery life.
6. **High mobility**: Connection can be maintained when device is moving at low and high speeds.
7. **High reliability**: High success probability that sent data arrives at receiver.
8. **High availability**: Network connections is always available.
9. **Higher security**: Additional security layers compared to older network generations (network slicing).

5G usage scenarios

Future usage scenarios enabled by 5G network capabilities[2]:

Enhanced Mobile Broadband (eMBB) to deal with hugely increased data rates, high user density and very high traffic capacity for hotspot scenarios as well as seamless coverage and high mobility scenarios with still improved used data rates (e.g. for high-resolution streaming).

Massive Machine-type Communications (mMTC) for the Internet of Things, requiring low power consumption at low data rates for very large numbers of connected devices (e.g. for using sensors without fixed electricity supply).

Ultra-reliable and Low Latency Communications (URLLC) to cater for safety-critical and mission critical applications (e.g. for management of electricity grids or automated driving cars).

Fig. 1. Main 5G network capabilities according to IMT-2020 standard [4] and 5G usage scenarios [3]. Higher security is not part of the IMT-2020 standard. However, network slicing is a 5G feature, which provides an additional layer of security compared to existing mobile network technologies. Network slicing is a technology which allows providing various, individually configured, virtual networks (network slices) based on one shared network infrastructure [5].

For Switzerland, having ratified the Paris Agreement and aiming to be climate-neutral by 2050, it is important to assess whether 5G will contribute to an increase of GHG emissions (e.g. due to the electricity consumption of network equipment) in the coming decades, or rather fosters new applications that can substantially contribute to climate protection. In the study reported here, we investigated both sides, guided by the following two research questions:

1. *Assessment of direct effects:* How much GHG emissions are caused by production and operation of 5G network equipment installed in Switzerland in 2030 (GHG footprint of 5G)?
2. *Assessment of indirect effects:* What are use cases which will benefit significantly from 5G mobile networks and what is their potential to contribute to the reduction of GHG emissions in Switzerland in 2030 (GHG abatement potential of 5G)?

This article is based on a project conducted by University of Zurich (Department of Informatics), Empa (Technology and Society Lab), Swisscom and Swisscleanteach [46], which has been extended with further analyses and discussions.

2 Materials and methods

2.1 Assessment of direct effects

The goal of the first part of the study was to estimate the global warming potential of 5G networks in comparison to 2-4G networks. To do so, we applied the Life Cycle Assessment (LCA) method as regulated in the ISO 14'040 series, using IPCC 2013 factors [44,45]. The functional unit is "1 Gigabyte (GB) of data transferred by the mobile network". Table 1 shows the (expected) mobile data traffic of Swisscom for 2020 and 2030.

We assessed the different mobile network generations (2G to 5G) operated by Switzerland's largest telecommunication network provider Swisscom, for the years 2020 and 2030. We included GHG impacts caused by producing and using mobile network equipment ("cradle-to-gate"). We excluded the end-of-life phase of network equipment, as well as office and technical buildings, as previous studies indicated that they are only minor contributors to mobile network GHG emissions [47–49].

We estimated, based on personal communication with experts, the type and amount of mobile network equipment rolled out in Switzerland according to the mobile network deployment strategy of Swisscom. The mobile network comprises the access, the core and the transport network (as shown in Fig. 2). Primary data on the types and numbers of devices comprising each of the network components and their related energy consumption was obtained from Swisscom and Ericsson. Data on the material composition of each device was collected from academic literature and expert opinions from Swisscom and Ericsson. Resulting GHG emissions caused along the life cycle of those components and materials were estimated using suitable life cycle inventory data from the ecoinvent database, version 3.6 [50].

To deal with the uncertainty about the future electricity mix in Switzerland, we modelled three different scenarios for 2030 (pessimistic, expected and optimistic) that differ with respect to the share of electricity from renewable sources with data from the database ecoinvent [50]: the pessimistic scenario having the lowest share of renewable energies, the optimistic the highest share, and the expected scenario lying in between.

For more details about the LCA calculations, including the used inventory data for the access, core and transport networks and the electricity mix scenarios, see [46].

Table 1. Mobile data traffic (million GB) transmitted by Swisscom 2-4G and 5G mobile networks in 2020 and 2030 (personal communication Swisscom).

Data traffic	**2020**	**2030**
Total data volume	544	5'042
Data volume transferred by 2-4G networks	539	1'008
Data volume transferred by 5G networks	5	4'033

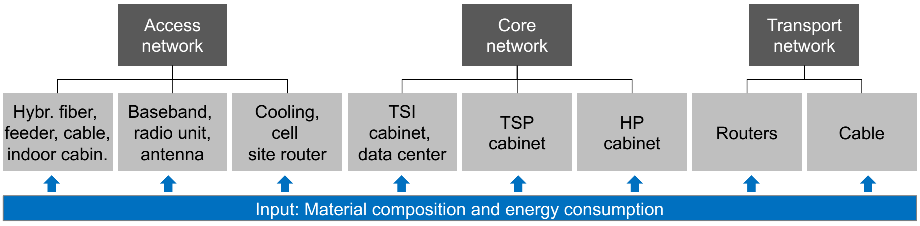


Fig. 2. System boundaries and investigated components of the mobile network.

2.2 Assessment of indirect effects

Since mobile networks have widely penetrated society, it is almost impossible to estimate indirect effects of 5G in general. For specific 5G-supported use cases, however, we can estimate GHG abatement potentials, e.g. by comparing the GHG impacts of processes before and after the (partial) adoption of the use cases [54].

In order to identify 5G-supported use cases, we first reviewed existing literature on 5G applications from academia, industry (e.g. network technology providers), standardization bodies (e.g. 3GPP) and industry associations (e.g. Next Generation Mobile Networks Alliance), aggregated similar use cases, harmonized terminology across use cases and clustered these into sectors. In total, we identified 26 use cases in the sectors transportation, manufacturing, farming, energy, buildings, entertainment/media, health and the public sector (for a detailed list, see [46]).

We selected four use cases (Table 2) for further investigation that best fulfilled the following two criteria in combination: (1) they are expected to benefit significantly from 5G mobile networks and (2) they have a high potential to reduce GHG emissions in Switzerland. In the selection, we considered insights from existing literature (e.g. [25]), from own previous studies (e.g. [28]) and from experts of the Swiss telecommunications sector.

To validate that each use case significantly benefits from 5G networks, we qualitatively analyzed existing literature on the mobile network requirements of the use cases and systematically assessed whether the capabilities provided by 5G networks (Fig. 1) provide benefits to meet these requirements.

Table 2. Description of selected 5G-supported use cases and GHG reduction levers.

Use case	Description
Flexible work	Working from everywhere and efficient virtual collaboration with colleagues and customers independent of location
Smart grid	Optimization and monitoring of electricity supply/demand processes
Automated driving	(Partly) automating the dynamic driving task in road transportation
Precision farming	Optimization of agricultural production processes

To quantify the GHG abatement potential of the four selected use cases, we applied a common approach in the field [51–53] that divides the task into the following five steps (see also Fig. 3). The approach is illustrated here with the example of Automated Driving (AD):

1. Identifying GHG abatement levers (e.g. increase of fuel efficiency of road transport vehicles through AD),
2. Estimating baseline emissions, i.e., the prospective emissions caused in 2030 with current patterns before the use case was realized (e.g. expected transport GHG emissions without significant adoption of AD),
3. Estimating the level of adoption of the use case in 2030, i.e., the share of the population that will adopt the use case (e.g. share of vehicles with AD technology in 2030),
4. Estimating the impact on GHG emissions per unit of adoption of the use case (e.g., increase in fuel efficiency through AD),
5. Estimating the expected rebound effects which counteract the abatements (e.g. increase in vehicle-miles travelled due to travel time cost reductions in individual transport).

To deal with the uncertainty about future developments and to show the potential influence of actions taken, we developed three scenarios ("pessimistic", "expected", and "optimistic") for the indirect effects in 2030 differing in assumptions about adoption rates, GHG impacts and electricity mixes in 2030. The scenarios are consistent with the direct effect scenarios mentioned in Section 2.1. The magnitude of the differences between the scenarios shows the uncertainty. We based the analysis on the data available from academic and industrial sources and additional interviews with experts from Switzerland and other countries (see [46] for more information).

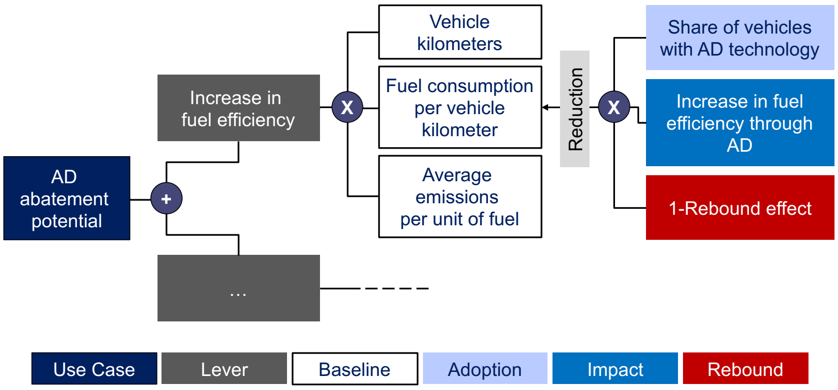


Fig. 3. Description of the calculation scheme using the example of the “Automated driving” use case based on [51, 54]. Rebound effects diminish the GHG reduction potential.

We considered direct rebound effects (price reductions of an energy service leading to increased consumption of the same service) based on insights from existing literature. We have excluded indirect rebound effects (price reductions of an energy service leading to increased consumption of other services), since their estimation is associated with even higher uncertainty that could only be reduced by using (valid) dynamic system models [54]. Generally, estimating rebound effects introduces substantial uncertainty as they involve demand elasticities, which are based on marginal values that differ across socio-economic contexts and are only valid for current absolute levels [54].

As the use cases depend on further ICT equipment besides 5G networks (e.g., smart grids require smart meters), we also roughly estimated the GHG emissions caused by production and operation of this additional equipment in 2030. For this "non-5G equipment", we estimated life-cycle GHG impacts of the devices based on their expected weight, lifetime and power consumption during operation, using device emission factors from ecoinvent [50]. For further details on all calculations as well as the underlying assumptions, see [46].

3 Results

3.1 Direct effects

GHG footprint per unit of data transmitted. Fig. 4 shows the GHG footprint of 2-4G networks in 2020, and of 4G and 5G networks in 2030 (2G and 3G networks are expected to be decommissioned by 2030) per unit of transmitted data based on the “expected” electricity mix. It shows that 5G mobile networks are expected to cause 85% less GHG emission in 2030 than 2-4G networks in 2020, and 44% less than 4G networks in 2030.

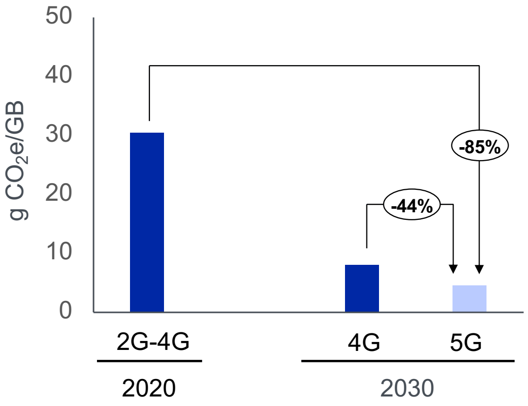


Fig. 4. GHG footprint of mobile networks per unit of transmitted data (1 GB) in 2020 and 2030 in the "expected" scenario.

Total GHG footprint per year. Fig. 5 shows the GHG footprint of 2-4G networks in 2020, and 4G and 5G networks in 2030 in total per year based on the "expected" electricity mix. It shows that the aggregated footprint of all mobile network technologies that are in operation increases by 20% between 2020 and 2030. This is because mobile data traffic is expected to increase even faster than the GHG efficiency of mobile networks. While 2-4G networks cause the major share of GHG emissions in 2020, by 2030 5G causes the major share of annual GHG emissions. This is because in 2020 most mobile data is transferred via 2-4G networks and in 2030 via 5G networks (Table 1).

The influence of the Swiss electricity mix on the future GHG footprint of mobile networks is shown in Fig. 6. Future changes in the Swiss electricity mix (i.e. higher share of renewable sources for electricity generation) obviously contribute to the reduction of GHG emissions caused by mobile networks. If mobile networks in 2030 would be operated with today's electricity mix, the GHG footprint would be roughly 10% higher than indicated in Fig. 5. The difference can be seen in Fig. 6 as the gap between the tops of the three narrow bars and the top of the light blue wider bar.

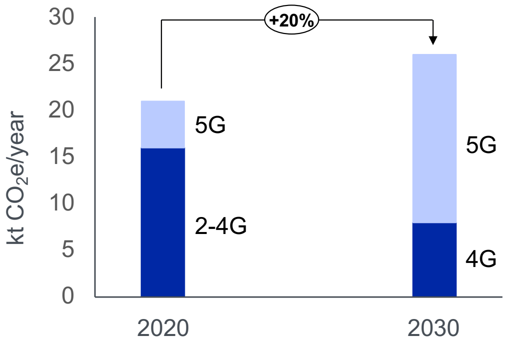


Fig. 5. Overall GHG footprint per year of mobile network technologies in 2020 and 2030 in the "expected" scenario.

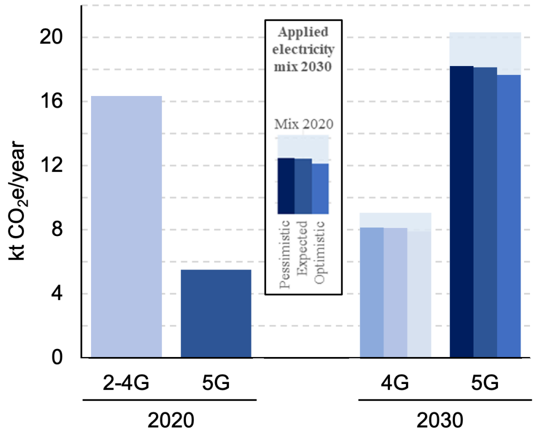


Fig. 6. GHG footprint of mobile networks per year in 2020 and 2030 by scenario. Whenever we show three bars, the left bar refers to the pessimistic, the middle bar to the expected, and the right bar to the optimistic scenario.

GHG footprint by life cycle stage and network component. Fig. 7 shows the share of GHG emissions by network component (i.e. access, core, transport network) and life cycle stages (i.e. production and use phase). For the 2-4G network in 2020, 60% of the GHG emissions are caused by the energy consumption during the use phase, with about 50% caused by the access network only. For the 5G network in 2030, the use phase is expected to cause 43% of total GHG emissions, 37% of which are caused again by the access network. This result confirms an observation by Malmodin et al. [20], who showed that the access network is the main source of GHG emissions in mobile networks.

While in 2020 more GHG emissions are caused by the use phase than during the production of the network components, this relationship turns around for 2030. One reason for this is the higher energy efficiency of the 5G network due to higher virtualization in the access network.

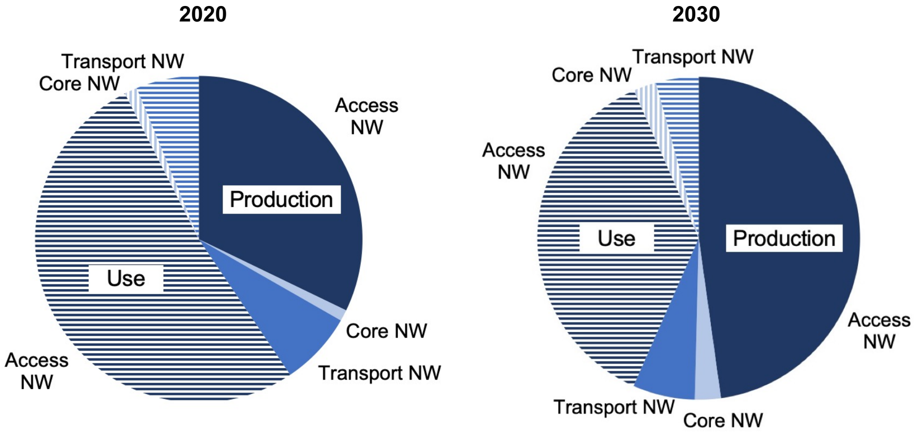


Fig. 7. GHG footprint of mobile networks per year in 2020 and 2030 by network component and lifecycle stage (NW=Network). The part with horizontal stripes represents the use phase, the part without stripes represents the production phase.

3.2 Indirect effects

5G capabilities and use cases. Table 3 summarizes the main 5G network capabilities which provide benefits to the selected use cases. Most important benefits, when looking at all four use cases, are ultra-low latency, the possibility to connect many devices, as well as high reliability, mobility, availability and security. For every use case, it is not a single capability but the combination of several capabilities within one wireless network standard, which provides the main benefit:

- *Flexible work*: High data rates combined with low latency and high reliability can enable (new forms of) virtual collaboration and provides access to large data volumes from almost anywhere (also in transport) at any time.
- *Smart grid*: Requires highly reliable, available and secure connection of many devices (e.g. sensors in the low-voltage part of the electricity grid) at low latency to ensure the stability of the grid as a safety-critical infrastructure.
- *Automated driving*: Requires highly reliable, available and secure data exchange between many moving vehicles at low latency (safety-critical).
- *Precision farming*: Requires the connection of many devices (e.g. sensors in fields) with low energy consumption because they are not connected to a fixed electricity supply network.

Table 3. Main benefits of 5G networks by 5G network capabilities and use case. “x” indicates the realization of the use case benefits of the respective network capability. For further details on the mobile network requirements by use case, please refer to [46].

Use case	**High data rates**	**High capacity**	**Ultra-low latency**	**Many devices**	**Low energy cons.**	**High reliability**	**High mobility**	**High availability**	**High security**
Flexible work	x		x			x	x		
Smart grid			x	x		x		x	x
Automated driving			x	x		x	x	x	x
Precision farming				x	x				

GHG abatement potential of 5G-supported use cases. Fig. 8 provides an overview of the estimated GHG abatement potential of the four selected use cases in Switzerland in 2030 by scenario. It can be seen that the uncertainty stemming from the various assumptions (regarding abatement potentials and rebound effects) that have to be made about the situation in 2030 adds up to a wide range between the extreme scenarios. In the optimistic scenario, the selected 5G-supported use cases could avoid roughly 2.1 Mt CO2e/year in Switzerland in 2030, in the expected scenario 0.6 Mt CO2e/year, and in the pessimistic scenario 0.1 Mt CO2e/year. Flexible work and smart grids provide the greatest potentials. The adoption of the four use cases is expected to be still relatively low by 2030. This means that the theoretical potentials—the abatement possible under the assumption of full adoption—are even higher.

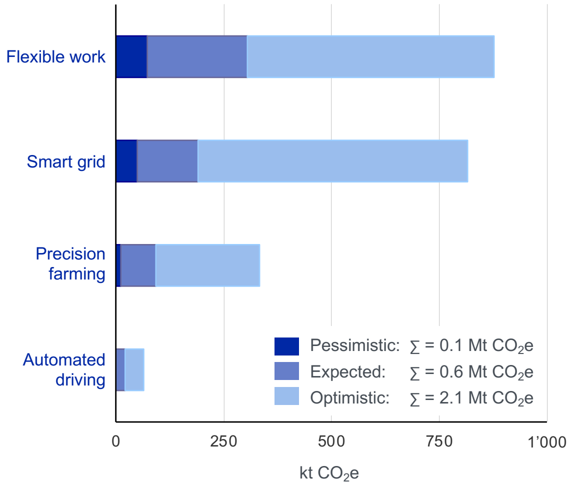


Fig. 8. GHG abatement potential by use case and scenario.

GHG footprint of non-5G ICT equipment. Fig. 9 provides an overview of the GHG footprint of the non-5G ICT equipment required to realize the use cases. Production and operation of this equipment causes up to 0.16 Mt CO2e/year in 2030 in the optimistic scenario, 0.08 Mt CO2e/year in the expected and 0.03 Mt CO2e/year in the pessimistic scenario.

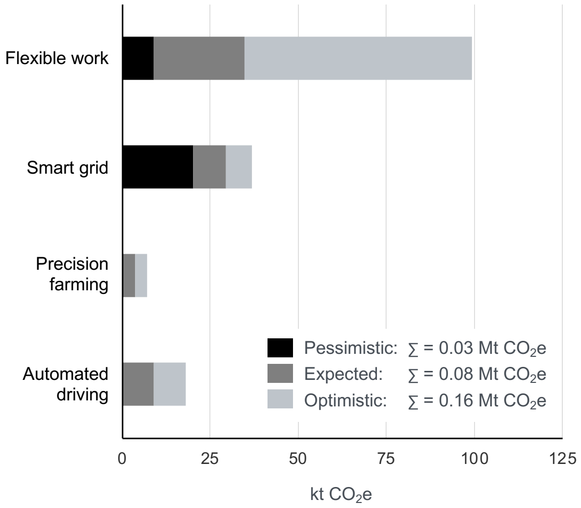


Fig. 9. GHG footprint of required non-5G ICT equipment by use case and scenario.

4 Discussion

4.1 Direct effects

Our estimation of the GHG footprint of 5G networks shows that production and operation of 5G network equipment installed in the Swisscom network will cause roughly 18 kt CO2e/year in 2030 (using the "expected" electricity mix). This represents less than 3% of the overall GHG footprint of the ICT sector in Switzerland (2.1 to 2.8 Mt CO2e in 2025 [28]), even if we roughly include the 5G networks of the two other telecommunication network operators in Switzerland (Sunrise, Salt). This result is not surprising, as ICT infrastructures (including networks) generally cause significantly less GHG emissions than the end-user devices used to access these infrastructures, provided that the foreign production of all devices is taken into account [28,33]. Given that 5G mobile networks will cause only a small fraction of the GHG footprint of the ICT sector in Switzerland, it seems advisable that measures to keep the GHG footprint of ICT in Switzerland small should not only focus on (5G) mobile network infrastructure, but target the whole ICT sector.

The 5G mobile networks are expected to cause less GHG emission in 2030 than 2-4G network in 2020, per unit of transmitted data. This result is in line with previous studies that showed that the energy efficiency of mobile networks (per GB) increases with each new generation. Malmodin et al. [20] estimate that 2G networks in Sweden in 2010 required 37 kWh/GB, whereas 3G networks required 2.9 kWh/GB.

If we consider the total amount of data transferred per year, 4G and 5G networks in 2030 together will cause 20% more GHG emissions than all mobile networks in 2020—this is because Swisscom's data traffic forecast for 2030 shows an expected increase (+827%) that is much higher than the increase in energy efficiency of the mobile network in the same time period. This confirms the observation of Pihkola et al. [55, p. 10] that while "energy efficiency per transferred GB has significantly decreased the total energy consumption at a mobile access network level might increase due to the higher increase of data usage".

4.2 Indirect effects

5G networks provide capabilities that provide benefits for use cases in various sectors. The four examined use cases (i.e. flexible work, smart grid, automated driving, precision farming) benefit specifically from the possibility to connect many devices, ultra-low latency, high reliability, mobility, availability and security provided by 5G networks. The older mobile network generations (i.e. 2G to 4G) currently in use do not provide all of the above listed capabilities to support these use cases. Some use cases can be realized with combinations of other wireless network technologies (e.g. WiFi-based AD plus LoRaWAN for precision farming). The key advantage of 5G is, however, that it combines the capabilities of several technologies into one single infrastructure. If each use case would be realized with (a combination of) different network technologies, the number of communication networks operated in parallel would increase, which would require more hardware and result in a higher energy consumption leading to higher bottom line environmental impacts, besides higher administrative complexity, and costs. Hence, to exploit the advantages of 5G from an environmental perspective, it is necessary to avoid the build-out and operation of several communication networks in parallel. Therefore, the phase-out of older generations of networks, which will become redundant when 5G networks are widely available, must be seriously pursued. But of course the safety and security aspects of redundant communication channels should also be taken into account [46].

In total, the four selected 5G-supported use cases could avoid roughly 2.1 Mt CO2e/year in Switzerland in 2030 in the optimistic scenario, 0.6 Mt CO2e/year in the expected scenario, and 0.1 Mt CO2e/year in the pessimistic scenario. Largest potentials lie in flexible work and smart grid. Looking beyond 2030, it is important to note that the adoption rates projected for 2030 are still relatively low, specifically for automated driving. This means that with a longer time horizon, the reduction potentials could increase further [46]. However, the use cases not only provide potentials for GHG abatement, but also risks for increasing GHG emissions. Table 4 shows the main opportunities for realizing the GHG abatement potential and risks for increasing GHG emissions. Most of them represent variants of the rebound effect.

4.3 Comparison of direct and indirect effects

A comparison of the direct and indirect effects of 5G networks on GHG emissions shows that the GHG abatement potentials of the four investigated use cases (0.1-2.1 Mt CO2e) is clearly larger than the GHG footprint of 5G networks (roughly 0.018 Mt CO2e) together with the additional non-5G equipment (0.03-0.16 Mt CO2e) in 2030. This result is not surprising, as several studies show that ICT‘s GHG abatement potential is in many cases much larger than its footprint, especially under optimistic assumptions [41]. However, the comparison between expected footprints and estimated abatement potentials has to be interpreted with care due to the limitations discussed in the following section.

4.4 Limitations

First, there are several sources of uncertainty in our assessments, including the limited availability of life cycle inventory data, the prediction of the future electricity mix, the estimation of the GHG abatement potential of the use cases, the need for additional ICT equipment to enable them (such as data centers) and the difficulty to define system boundaries in the IT world, as well as the estimation of future rebound effects.

Second, the estimation of GHG abatement potentials in the present study is focused on a small set of 5G-supported use cases. These provide evidence that GHG abatement potentials exist that are clearly larger than the 5G footprint. Still, there are additional 5G-supported use cases that could provide additional GHG abatement potentials such as industry automation.

Third, our selection of use cases was driven by the focus on GHG abatement potentials, i.e., we selected use cases that are promising with regard to the reduction of GHG emissions. We cannot exclude that there are use cases of 5G that can have an increasing effect on GHG emissions; systematically identifying those would yield a different result.

Also, we did not consider many indirect rebound effects, neither induction effects [7] that could lead to an increase in GHG emissions, because they depend on many factors that are beyond the scope of our study. We encourage researchers to conduct complementary studies that focus on the risks through which 5G could lead to an increase of GHG emissions, and suitable mitigation measures.

We are also aware of the fact that 5G is a beneficial, but not a necessary condition for the realization of the use cases discussed. We could show that 5G supports the realization of the selected use cases because it unites many capabilities required for the use cases in one network technology. We cannot exclude the possibility to realize the use cases by combining other network technologies (e.g. fixed networks, Wi-Fi, 4G).

Table 4. Main levers for realizing GHG abatement potential and risks that should be mitigated.

Use case	Main GHG abatement levers	Main risks for increasing GHG emissions
Flexible work	• Reduction of commuting distances and frequencies • Reduction of business trips • Reduction of office space	• Increased virtual collaboration induces additional business trips • Individuals spend saved time and money on GHG-intensive activities, goods or services (e.g. travel) • (Heated) residential space increases due to working from home and (heated) office spaces at employer offices does not decrease
Smart grid	• Built out of renewable energy sources (e.g. wind, sun) • Dynamically adapting electricity demand according to availability of electricity from renewable energy sources	• Electricity consumers spend saved money on consumption of additional electricity or other GHG-intensive goods or services
Automated driving	• Increasing fuel efficiency through automated driving • Reducing number of vehicles and vehicles-miles traveled by increasing utilization of vehicles (e.g. through automated public transport)	• Increased attractiveness of car transport and access for underserved population increases vehicle-miles travelled and cannibalizes other, more GHG-efficient, transport modes
Precision farming	• Increasing productivity in livestock farming (e.g. through disease detection) • Reduction of agricultural inputs (e.g. fertilizers, water)	• Efficiency increase are used to increase yield and not to reduce use of agricultural inputs and GHG emissions

5 Conclusions

In the present study, we assessed the GHG footprint of 5G and existing mobile network technologies in Switzerland prospectively for the years 2020 and 2030 (direct effects) and the extent to which 5G will be able to crucially support use cases with high GHG abatement potential, and the size of this abatement potential (indirect effects).

By 2030, the 5G network operated by Swisscom is estimated to cause 0.018 Mt CO2e GHG emissions per year from a life-cycle perspective. Per unit of transmitted data, this corresponds to a reduction of 85% compared to today's mobile networks. In absolute terms, however, we expect the emissions to be slightly higher because the prospective increase in data traffic over-compensates for the increase in GHG efficiency, even under the assumption that the older networks will be phased out. Still, the most climate friendly way to meet the expected future increase in demand for mobile data traffic is to use 5G mobile networks, and phase out older network technologies.

5G networks also provide capabilities that can create significant benefits for use cases in transportation, manufacturing, farming, energy, buildings, entertainment and media, health and the public sector. Four of these use cases (i.e. flexible work, smart grid, automated driving, precision farming) have been investigated in detail and we found that their potential to contribute to the reduction of GHG emissions in Switzerland is much larger than the footprint of 5G. These use cases benefit specifically from the ultra-low latency, the possibility to connect many devices as well as the high reliability, mobility, availability and security provided by 5G. Current 4G mobile networks can only provide these capabilities in combination with other network technologies which perform better on requirements regarding mobility, latency, reliability or availability. Hence, 5G has the advantage of meeting the requirements of many use cases with one single mobile network technology, and making older, less GHG-efficient, technologies obsolete.

In order to put 5G at the service of climate protection, measures should be taken in two fields. First, the GHG footprint of 5G should be kept small, by:

1. Rolling out only as much 5G infrastructure as required
2. Running 5G with electricity from renewable energy sources
3. Phasing out older network technologies (e.g. 3G, 4G) once 5G is widely available.

However, it is important to address all ICT infrastructure because 5G networks will be responsible for only a small fraction of the total GHG footprint of the ICT sector.

Second, the GHG abatement potentials created by 5G-supported use cases should be systematically exploited, e.g. by creating conditions that target GHG reductions through flexible work models, new mobility services, renewable energy sources, and climate-friendly forms of farming. It is important to create a regulatory framework that mitigates the risk of rebound effects, e.g. by getting the price of GHG emissions right. If no targeted action towards such framework conditions is taken, there is a risk that the reductions will remain small and that rebound effects will compensate or even over-compensate for possible GHG emission reductions.

The conclusion for practice is – as often in technology assessment – that the final outcome will depend very much on the political will to steer the development into the direction of a politically defined target such as a net GHG emissions reduction. The technology as such will not decide about the direction of change.

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